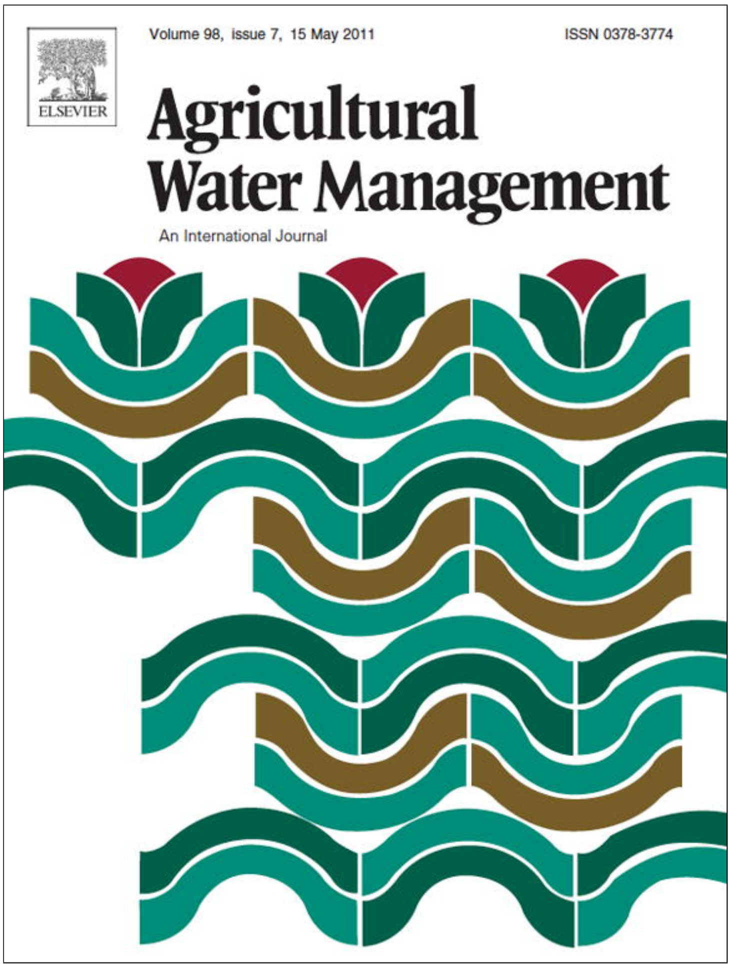
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The downstream externalities of harvesting rainwater in semi-arid watersheds: An Indian case study

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ABSTRACT

Water-related investment projects affect downstream water availability, and therefore should account for these externalities. Few projects do, however, owing to lack of awareness, lack of data and difficulty in linking upstream investments to downstream effects. This article assesses the downstream impacts of rainwater harvesting in a semi-arid basin in Southern India, focusing on the trade-offs that arise when crop water use is re-allocated from a downstream surface water irrigation system to groundwater irrigated agriculture upstream. The results indicate that the downstream impacts are considerable and that net benefits are insufficient to pay back investment costs. Further research is required to reduce the uncertainties in the water balance of irrigation systems at basin level, to account for the inter-annual variability of crop water availability and to elaborate the wider welfare effects.

1. Introduction

Water-related investments often have significant impacts downstream and although it is generally agreed that the downstream impacts of water-related investments should be accounted for, few studies do (Shah and Raju, 2001; McKinney et al., 1999). Exceptions are Chakravorty and Umetsu (2003) and Rosegrant et al. (2000). An important reason is that it is difficult to get basin-wide data on water flows and economic returns to water and to establish a clear linkage between (upstream) investments and (downstream) effects. Using a combination of hydrological and socio-economic data, this article evaluates the basin wide welfare impacts of rainwater harvesting in semi-arid India by assessing the increase in (groundwater irrigated) agricultural production upstream and the decrease in (surface water irrigated) production downstream, and accounting for rainwater harvesting investment costs.

Rainwater harvesting investments are an integral part of the watershed development (WSD) program, which is one of the main rural development programs in India (Kerr et al., 2002). WSD programs typically include investments in bunds and trenches to increase infiltration of rainwater, and gully plugs and small dams to store water and enhance recharging of local groundwater aquifers. WSD investments may also include soil conservation, reforestation and land-levelling investments, but given that in the case study considered such investments consisted for less than 5% of the total budget, our analysis will only consider the impacts of rainwater harvesting at sub-basin scale.

Investments in rainwater harvesting are highly popular in India's semi-arid regions, since they help to recharge groundwater aquifers (Batchelor et al., 2003). Water levels in aquifers in several locations in India have been declining due to the rapid increases in groundwater irrigation, which was triggered by technological changes, like tubewell irrigation, and higher returns on irrigated crops (Chandrakanth et al., 2004). Harvesting rainwater to recharge groundwater aquifers can help sustain more water intensive agri-

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cultural production, but is likely to also reduce the flow of surface water to users downstream. When downstream users have access to the recharged aquifers there are no negative externalities, but given the often-large distances between up and downstream users in a sub-basin, the benefits of groundwater recharge are usually not shared. Also, geological features might not be conducive to groundwater sharing, for example, if the subsurface consists of fractured hard rock aquifers, which tends to limit the lateral flow.

Upstream use will have minimal impact in river systems that have surplus flow to the ocean that is unallocated for other uses. In hydrologically closed basins, where all water is allocated for some use, consumptive use upstream will impact downstream users. Studies evaluating the welfare impacts of WSD have largely ignored these potential downstream externalities,[1] and generally conclude that WSD is welfare enhancing since local benefits exceed WSD investment costs (see for example Joshi et al., 2005; Kerr et al., 2002; Diwakara and Chandrakanth, 2007). This article evaluates the welfare impacts of WSD at sub-basin level, accounting for upstream benefits, downstream losses and WSD investment costs. By welfare we refer to economic well-being and we measure welfare impacts by assessing changes in the economic value of crop water use at sub-basin scale. Specifically, we consider changes in producer surplus resulting from a re-allocation of crop water use caused by rainwater harvesting upstream. Welfare impacts are positive when the total gain in producer surplus exceeds WSD investment costs. When welfare impacts are negative there could be other reasons to promote WSD, for example equity concerns, but in this article we only consider efficiency trade-offs.

Two factors are expected to determine the total welfare effect. First, hydrological analysis has shown that rainwater harvesting reduces the downstream flow of surface water by allowing more of the rainfall to be absorbed in the soil profile and recharged to local aquifers upstream (Madsen, 1988; Ramireddygari et al., 2000; Burt, 2002; Lasage et al., 2008). This increases the availability of (irrigation) water in upstream regions, but when water is scarce it reduces the availability of water downstream (Batchelor et al., 2003). Second, rainwater harvesting may increase the efficiency of water use, as using water 'where it falls', and recharging it to soils and groundwater aquifers, can avoid some of the storage and transmission (evaporation) losses associated with transporting water to reservoirs downstream (Honore, 2002).

Using a basic economic model we assess whether WSD benefits are sufficient to compensate downstream losses and pay-back investment costs. Based on the observed changes in hydrology in a sub-basin with WSD activities, we simulate the impact of changes in water availability on cropping patterns and estimate the change in agricultural value produced. We compare outcomes with the costs of WSD investment and conduct a Monte Carlo simulation to test the robustness of our results.

It is important to note that investments in rainwater harvesting can have other impacts than changes in the availability of water alone. Increases in soil moisture can help improve the productivity of rainfed agriculture, and bunds and dams can help reduce soil erosion as well. In mountainous areas, the main benefits of WSD are often reductions in soil erosion (Goel and Kumar, 2005; Kerr et al., 2002) and WSD is generally promoted for improving the productivity of rainfed crops (Sahrawat et al., 2010). Targeting WSD to soil conservation might actually cause positive externalities downstream, as it tends to improve water quality and reduce sedimentation, but given the low elevations and low slopes of the case study region, few investments in soil conservation were made. Increased productivity of rainfed agriculture also causes fewer externalities for downstream users (Batchelor et al., 2003), but given the low expected returns to rainfed agriculture in semi-arid regions, WSD investments are usually targeted to groundwater recharge instead (Bouma and Scott, 2006). This is confirmed by other studies in the region (Kerr et al., 2002; Chandrakanth et al., 2004; Diwakara and Chandrakanth, 2007) and justifies the focus on WSD impacts in terms of changes in the availability of (irrigation) water alone.[2]

The dataset we use to assess the downstream externalities is a combination of government statistics regarding WSD investment, cropping patterns and agricultural production costs, and estimates of crop evapotranspiration from previous investigations (in particular Bouwer et al., 2008). In addition, we use hydrological information about the changes in mean annual reservoir inflow and government estimates of the additional storage capacity created by the WSD investments upstream.

The structure of the article is as follows. In the next paragraph we introduce the case study. We then introduce our model after which we present the main results. Finally, we test outcome robustness with a Monte Carlo simulation, discuss the wider welfare implications and conclude.

2. Case study

To estimate the downstream externalities of rainwater harvesting in semi-arid watersheds, we consider the case of WSD in the Krishna basin. The Krishna basin is one of India's major river basins located in the Southern peninsula and is spread over three states. Water is scarce in the basin and only a small amount of water still reaches the sea (Biggs et al., 2007). In the downstream part of the Krishna basin large investments have been made in surface water irrigation. Upstream of the irrigation schemes, on the Deccan plateau, agriculture was historically rainfed, but over the last decades substantial investments were made in groundwater irrigation. The intensification of water use on the Deccan plateau resulted in a reduced flow of surface water to the downstream irrigation reservoirs (Amarasinghe et al., 2004; Biggs et al., 2007).[3] It also resulted in a depletion of local groundwater aquifers, in response to which substantial WSD investments were made. Given that most of the basin is characterized by hard rock geology, lateral subsurface hydraulic connectivity is limited at the regional scale, so the benefits of these investments via groundwater recharge are not shared between up and downstream users. Thus, WSD might be causing negative externalities downstream.

[1] In the payments for ecosystem services (PES) literature there have been a couple of studies assessing up-downstream externalities in a watershed context, like for example, Kosoy et al. (2007) and Quintero et al. (2009) on water quality and sedimentation and Fisher et al. (2010) on water allocation. The PES framework is however less suitable for analyzing the downstream externalities of rainwater harvesting, since the externalities of decision-making are implicitly internalized by having the government invest both in upstream rainwater harvesting and in surface water irrigation systems downstream.

[2] Unlike WSD investment programs that target the productivity of rainfed agriculture, programs that focus on rainwater harvesting and groundwater recharge only benefit those with access to groundwater irrigation. In some villages, only few households have access to irrigation and the welfare impacts of WSD are unequally spread (Kerr et al., 2002). The reason why WSD programs still target groundwater recharge are twofold. First, households with access to irrigation are usually the most influential (Kerr et al., 2002). Second, farmers with no irrigation are often reluctant to make WSD investments on their land, given that the returns to investment are highly uncertain and that most of their income comes from other sources, like off-farm employment, which raises their opportunity costs (Bouma and Scott, 2006).

[3] In fact, the main explanation for the reduced flow of water to the downstream surface water irrigation reservoirs are investments in major surface water irrigation reservoirs further upstream. For example, in the Krishna basin the volume of large reservoirs for surface water irrigation expanded in volume between 1947 and 2000 by about 1200% (Bouwer et al., 2006). In comparison, the impact of WSD has been much less, but WSD investments are still causing part of the reduced inflow downstream (Batchelor et al., 2003).

We focus the analysis on one of the sub-basins of the Krishna basin, the Musi sub-basin. The upstream part of the basin is dominated by rainfed crops and groundwater irrigation, and the downstream part by large surface water irrigation schemes, like the Nagarjuna Sagar irrigation scheme. The sub-basin is atypical because it includes the city of Hyderabad with approximately 7 million inhabitants the fifth largest city of India. The city derives its drinking water from several reservoirs in the Musi sub-basin, including the Osman and Himayat reservoirs. In the catchment of these reservoirs, a combined area of 2111 km^2, substantial WSD investments were made. This, together with a rapid increase in groundwater irrigation, contributed to a reduced mean annual inflow in the two reservoirs. To avoid impacts on urban water demand, the city responded to this reduced inflow by pumping more water from the Nagarjuna irrigation reservoir, 120 km downstream. Given the scarcity of water in the Nagarjuna irrigation command area, this extra abstraction from Nagarjuna reservoir is likely to have caused a loss of irrigated area downstream (Van Rooijen et al., 2005; Gaur et al., 2007). Hence, we define 'upstream' as the producers in the catchment area of Osman and Himayat reservoir and 'downstream' as the producers in the command area of Nagarjuna Sagar irrigations reservoir, 120 km downstream. Please note that the cities' water use and the wastewater irrigation associated with urban return flows are not part of our analysis.[4]

Data on the inflow of surface water to the two drinking water reservoirs show that between 1975 and 2002, the annual inflow of water to Osman and Himayat reservoirs decreased by a total of 17 million cubic meters (MCM) (Biggs, 2005): between 1970 and 1985 an average rainfall of 600–700 mm rainfall was sufficient to fill up the reservoirs, but in the period 1985–2003 this changed to a minimum rainfall level of 800–900 mm (Biggs, 2005).[5] Interestingly, government data on WSD investment in the catchment area of the two reservoirs indicate that between 2000 and 2005, in the most conservative estimate (i.e., assuming structures fill up once a year), an additional 15 MCM of water storage was created upstream.[6] Although the reduction in inflow started prior to the WSD investments, WSD is expected to have deepened and extended the reduction of surface water inflow: studies in the region assessing the impact of groundwater recharge investment show that WSD increases local groundwater recharge by 25–70% (Chandrakanth et al., 2004) and that without WSD the area irrigated with groundwater seriously declines (Ratna Reddy, 2005) (Fig. 1).

The government data regarding WSD investments in the Musi sub-basin (see also footnote 5) indicated that the costs of creating the additional 15 MCM of water storage were approximately 8 million USD. Since investments cover the entire catchment of the two reservoirs, in which approximately 80,000 ha is cultivated, this translates into an average investment cost of USD 100/ha.

Table 1 presents land use and cropping patterns in the Musi sub-basin. It is important to note that whereas WSD investment programs are usually targeted at remote watersheds, often with relatively low value agriculture, the value of agricultural production in the upstream part of the Musi sub-basin is relatively high. The main land use in the upstream region is vegetable and fruit production, which are both high value crops. The high value of agricultural production in the Musi-sub-basin can be explained by the proximity of Hyderabad city, i.e., a large demand for high value fruits and vegetables and low transportation costs.

The atypical character of agricultural production in the upstream part of the sub-basin is likely to influence the outcomes as it increases the benefits of WSD. This might not be very representative for WSD in general, but when interpreted as an extreme example of highly profitable WSD it is interesting to see whether WSD benefits are sufficient to compensate downstream losses and pay-back WSD investment costs.

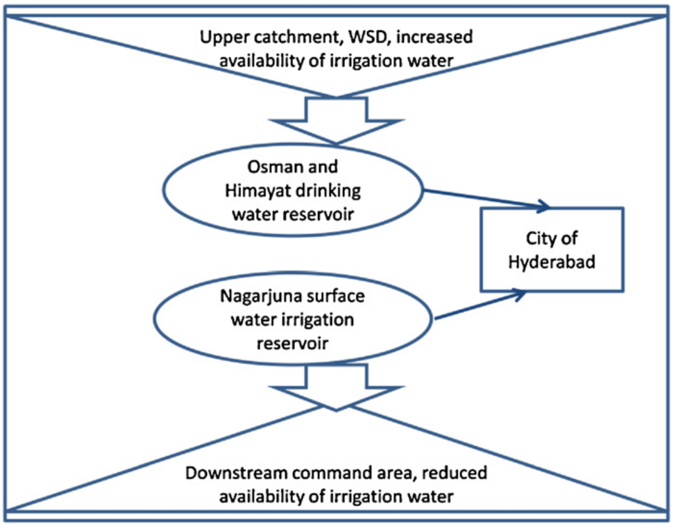

Fig. 1. Schematic representation of water flows in the Musi sub-basin.

Table 1
Land use and cropping patterns in the Musi sub-basin.

	Land use (ha)
Upstream	
Rice	10,585
Vegetables, fruit, spices, cotton	26,712
Oilseeds, maize and pulses	19,443
Downstream	
Rice	251,255
Cotton, vegetables, fruit, spices	274,625
Oilseeds, maize and pulses	218,513

Government of India, www.indiastat.com and District Statistical Handbook 2000–2001.

3. Model

To evaluate the costs and benefits of WSD in the Musi sub-basin, we need to estimate the economic value of crop water use up- and downstream. Since markets for water are missing in the Krishna basin, we need to infer the economic value of crop water use from the value of agricultural production. Generally, agro-economic models show water to be a crucial determinant of agricultural production (Cai et al., 2001). More water increases agricultural yields, and better access to irrigation water generally allows for the production of more water intensive, higher value crops. In line with Rosegrant et al. (2000), one of the few other studies that evaluate the welfare impacts of water re-allocation at basin scale, we use the producer surplus approach to assess the economic value of crop water use.

The producer surplus approach estimates the change in producer surplus resulting from a change in resource use, assuming that all other production factors are accounted for in the production

[4] WSD did increase the costs of urban water supply. This is, however, unlikely to have affected urban water demand, as consumers do not pay the variable costs of water use. Including the city's additional costs in the analysis lowers the welfare impact of WSD.

[5] Average annual rainfall is approx. 890 mm between 1974 and 2003.

[6] Data on WSD investments in the catchment area were taken from the Government of Andhra Pradesh. Investments primarily focused on groundwater recharge, with investments mostly in small reservoirs and dams. For each investment the data reported the amount of storage created. Adding up the storage created in the catchment of the two reservoirs, and assuming structures fill up once a year resulted in the estimate of an additional water storage capacity of 15 MCM/year.

costs and stay the same (the 'ceteris paribus' assumption). Considering that WSD investments in rainwater harvesting merely change the availability of (irrigation) water this is not an unreasonable assumption. Using the producer surplus method has an advantage over, for example, a willingness to pay approach, in that data are more readily available. The producer surplus method also has an important drawback in that it assumes that markets are functioning perfectly and that except for water, no other missing markets exist. Especially in India's rural regions, this may not always be the case, but by focusing the analysis on commercial crops like vegetables, rice, cotton and oilseeds, we try to avoid some of the problems associated with missing markets. Impacts in terms of changes in consumer surplus are not expected since most agricultural prices in India are fixed.

To estimate how changes in the allocation of crop water use affect the producer surplus, we develop a basic economic model. We assume that there is a social planner who wants to maximize basin welfare based on the following function:

$$max\Pi = \sum_{i=1}^{3}\sum_{j=\mathrm{u,\,d}} p_{ij}A_{ij}e_{ij}^{\alpha_j}h_{ij}^{1-\alpha_j} - \beta_j h_{ij}^{\gamma_j} \quad \text{with } 0 \le \alpha \le 1 \text{ and } \gamma > 1 \tag{1}$$

with $i = 1, 2, 3$ for the different crops and, $j = \mathrm{u, d}$ for location in the sub-basin (up or downstream), p for net prices (i.e., domestic market prices minus crop production costs), e for crop water use (volume), h for cropped area, A is a technical coefficient reflecting crop production technology, α the water intensity of agricultural production and $\beta_j h_{ij}^{\gamma_j}$ a cost function reflecting increasing production costs per ha. Crop water use e includes only water that is lost from the basin through crop evapotranspiration, and does not include additional water applied to the soil in excess of evaporative demand. Note that e includes water derived from both rainfall and irrigation water. Any irrigation water applied in excess of the crop evapotranspiration requirement is assumed to remain in the basin as either groundwater or surface water.

The direct costs of production are included in net prices, but an additional production cost figure was added to reflect increasing costs of labour during peak labour demand (harvest). Since labour markets and production costs differ between up and downstream regions, the cost function $\beta_j h_{ij}^{\gamma_j}$ is location specific. The water intensity of agricultural production α is also location specific and reflects local climatic conditions.[7] The model is static because the analysis focuses on a flow variable (water). WSD might have other, stock-related, impacts but given that in the sub-basin considered most investments concern rainwater harvesting, we expect the main impact of WSD to be a re-allocation of water, the economic value of which we can capture with a static model. Besides, we do not have the data to calibrate a dynamic model and assess potential stock effects.

We use the assumption of a social planner because in the Indian context the government coordinates agricultural water demand and supply. Water markets do not exist and the allocation of water is largely controlled by the state. An exception is the investments undertaken in groundwater irrigation, which are largely private and lack state coordination. However, given that without (public) WSD investment the area irrigated with groundwater would likely decrease, we might consider the allocation of groundwater to be implicitly state-controlled (or at least state-influenced) as well. The main constraint that the social planner faces is that total crop water demand cannot exceed crop water supply (E_j):

$$E_j - \sum e_{ij} = 0 \tag{2}$$

Here, the total supply of crop water use is measured as the actual crop water use in the 2000–2001 water year (June 2000–May 2001) based on observed cropped areas and crop water use estimates (see below). Since E_j includes total crop water use, including from rainfall and irrigation water, the model implicitly assumes that rainfall and potential evapotranspiration are constant. The total amount of rainfall recorded near Hyderabad in 2000–2001 (710 mm) was slightly lower than the average over 1974–2003 (890 mm), so the results apply for years that are slightly drier than average. The impact of inter-annual variability in rainfall on crop water use is not addressed, but would be a useful future study.

With a fixed amount of water, WSD investments increase total crop water use upstream and reduce total crop water use downstream. Since WSD is expected to increase water use efficiency by reducing the evaporation losses associated with transporting and storing water in large irrigation reservoirs, total crop water supply upstream increases more than it decreases downstream. In the analysis we will assume an efficiency gain of 20%. Given the arbitrariness of this assumption we also consider a situation with no efficiency gain.

The social planner maximizes welfare by setting marginal benefits equal to marginal costs. To get an explicit function for the shadow price of water μ, we use Eqs. (1) and (2) to form the Lagrangian function of which the first order conditions are:

$$\frac{\partial L}{\partial e_{ij}} = p_{ij}A_{ij}\alpha_j e_{ij}^{\alpha_j-1}h_{ij}^{1-\alpha_j} - \mu_j = 0 \tag{3}$$

$$\frac{\partial L}{\partial h_{ij}} = p_{ij}A_{ij}e_{ij}^{\alpha_j}(1-\alpha_j)h_{ij}^{-\alpha_j} - \beta_j\gamma_j h_{ij}^{\gamma_j-1} = 0 \tag{4}$$

$$\frac{\partial L}{\partial \mu_j} = E_j - \sum e_{ij} = 0 \tag{5}$$

Solving Eq. (3) for h_{ij} we get,

$$h_{ij} = \left(\frac{\mu_j}{p_{ij}A_{ij}\alpha_j}\right)^{1/(1-\alpha_j)} e_{ij} \tag{6}$$

Substituting Eq. (6) into Eq. (4) we get the following expression for the volume of crop water use e_i that maximizes welfare:

$$e_{ij} = \mu_j^{1-\gamma_j-\alpha_j/(1-\alpha_j)(\gamma_j-1)}\left(\frac{1-\alpha_j}{\beta_j\gamma_j}\right)^{1/(\gamma_j-1)} \alpha_j^{\gamma_j+\alpha_j-1/(1-\alpha_j)(\gamma_j-1)} p_{ij}A_{ij}^{\gamma_j/(1-\alpha_j)(\gamma_j-1)} \tag{7}$$

Using Eqs. (5) and (7) we get an expression for the shadow price of water μ:

$$\mu_j = E_j^{(1-\alpha_j)(\gamma_j-1)/1-\gamma_j-\alpha_j}\alpha_j\left(\frac{\beta_j\gamma_j}{1-\alpha_j}\right)^{1-\alpha_j/1-\gamma_j-\alpha_j} W_j^{(1-\alpha_j)(1-\gamma_j)/1-\gamma_j-\alpha_j} \quad \text{with} \quad W_j = (p_{1j}A_{1j})^{\gamma_j/(1-\alpha_j)(\gamma_j-1)} + (p_{2j}A_{2j})^{\gamma_j/(1-\alpha_j)(\gamma_j-1)} + (p_{3j}A_{3j})^{\gamma_j/(1-\alpha_j)(\gamma_j-1)} \tag{8}$$

From which it follows that:

$$e_{ij} = \frac{E_j}{W_j}(p_{ij}A_{ij})^{\gamma_j/(1-\alpha_j)(\gamma_j-1)} \tag{9}$$

and

$$h_{ij} = \left(\frac{E_j}{W_j}\right)^{\gamma_j/1-\gamma_j-\alpha_j}\left(\frac{\beta_j\gamma_j}{1-\alpha_j}\right)^{1/1-\gamma_j-\alpha_j}(p_{ij}A_{ij})^{1/(1-\alpha_j)(\gamma_j-1)} \tag{10}$$

[7] In fact, the water intensity of agricultural production also differs per crop, but with crop specific water intensity variables the model becomes analytically unsolvable. Hence, we assume similar water intensities per crop and discuss the potential biases resulting from this in the discussion of results.

Table 2
Crop yield and crop water use (ET) data.

	Yield (kg/ha)	ET (m^3/ha)	Data Source
Maximum			
Upstream			
Rice	3200	8748	Yield data from Government of India, 2000–2002 at www.indiastat.com
Vegetables	20,000	6607	
Oilseeds	1000	4862	
Downstream			
Rice	3600	8868	ET calculated using the FAO 56 method (Allen et al., 1998)
Cotton	380	5546	
Oilseeds	1200	4690	
Actual			
Upstream			
Rice	2550	4050	Yield data from Government of India, 2000–2002 at www.indiastat.com.
Vegetables	13,500	3000	
Oilseeds	750	3220	
Downstream			
Rice	3250	4200	ET data from Bouwer et al. (2008)
Cotton	322	4680	
Oilseeds	1000	3220	

Ideally, we would have used our empirical data to estimate the model econometrically but given the limited data available, we had to use a more experimental approach.

First, we estimated A and α using data on actual and optimal crop evapotranspiration and crop yields. We consider three crop groups, in line with local cropping patterns (see Table 1). The first, most water-intensive crop is paddy (rice). For the second crop group we use vegetables as reference crop group upstream and cotton as reference crop downstream. For the third crop group we use oilseeds as the reference crop. Using two data points (1) actual crop water use and crop yield and (2) optimal crop water use and maximum crop yield, we estimate α and A for up- and downstream locations. In Table 2 we present the data used to estimate α and A, with crop yield figures for Andhra Pradesh.

We calculated the optimal crop water requirements with the FAO 56 method, based on the Penman–Monteith equation, using information about local climatic conditions (temperature, wind speed, relative humidity and solar radiation) to estimate maximum crop water use up- and downstream (see Allen et al., 1998 for details). Assuming that all other production requirements are met, supplying crops with the optimal crop water requirement results in maximum yields. To get a realistic estimate of the maximum crop yields, we took the highest yields encountered in the region. We took the figures on actual water use from Bouwer et al. (2008), which uses a water balance model and thermal satellite imagery to estimate actual evaporation for different crops in the Musi basin. Locations of different cropping patterns were established from satellite imagery and ground-truth information, and the basin water balance was validated with streamflow data.[8] By relating the evaporation estimates to temporal and spatial variation of remotely sensed surface temperatures, an estimate was made of crop-specific seasonal water use in both locations.[9] Although considerable uncertainties are associated with these estimates, they are likely to lie close to the actual crop evaporation rates in the Musi basin, for two reasons. First, estimates from Bouwer et al. (2008) were based on annual water balance calculations constrained by observed precipitation and observed basin outflow. Second, the evaporation estimates for open water and irrigated crops approximated pan evaporation and empirical evaporation rates for irrigated crops. We used multi-year average crop yields as an estimate for actual crop yields (Table 2).

[8] We do not account for the inter-annual variability of water use as our analysis is based on the long-term, average tradeoff. Inter-annual variability might affect outcomes in very dry/wet years, but we could not account for such effects in our analysis.

Table 3
Net returns per ha-actual yields (USD/ha).

Upstream		Downstream	
Rice	127.50	Rice	162.50
Vegetables	540	Cotton	290
Oilseeds	52.50	Oilseeds	70

Government of India, 2000–2002 at www.indiastat.com.
Exchange rate: 1 USD = Rs. 50.

Table 4
Simulated versus actual cropping patterns (in ha).

	Actual	Simulated
Upstream		
Rice	10,585	12,972
Vegetables, fruit, spices, cotton	26,712	21,185
Oilseeds, maize and pulses	19,443	17,975
Downstream		
Rice	251,255	251,245
Cotton, vegetables, fruit, spices	274,625	274,643
Oilseeds, maize and pulses	218,513	218,503

Second, we calculated total crop water use based on the actual cropping patterns in the basin (District Statistical Handbook 2000–2001) and actual crop water use (Tables 1 and 2).

Third, we used information on farm harvest prices, production costs, and average crop yields for the state of Andhra Pradesh (www.indiastat.com, 2000–2002) to estimate the net average returns per ha, see Table 3. Since data were not available for a single year, we used multi-year averages. Please note that the prices of rice, oilseeds and cotton are fixed.

Using an Excel-based optimization model we estimated β and γ by minimizing the difference between actual and simulated cropping patterns. Results are presented in Tables 4 and 5. Since we had to use average water intensity factors instead of crop-specific water intensity factors, we had to re-estimate the crop specific values for A. Although we tried to stay as close as possible to the original crop-specific estimates of α and A, there was room to assume different values for A. We used the highest estimate for A as benchmark for the re-estimation of A, based on the average water intensity factor α.

As Table 4 shows, the model underestimates upstream vegetable and oilseed production and (slightly) overestimates the upstream production of rice. This is caused by the fact that instead of crop specific water intensity factors we use a location specific, average water intensity indicator α.

[9] The analysis found evidence of relatively low evaporation rates from irrigated crops compared with the expectation from reference evaporation: estimates of actual evaporation from irrigated rice are 39–45% less than predicted by crop coefficients for an unstressed crop. This is most likely because, even in irrigated areas, only 70–80% of the area is actually irrigated, but it could also be due to low evaporation from the irrigated crop itself due to sub-optimal growing conditions or interruptions in water application (Bouwer et al., 2008). This effect may increase both our estimated upstream and downstream crop water use.The ratio of measured to potential ET is similar upstream and downstream.

Table 5
Key parameters in the model.

	Up	Down
α	0.50	0.53
A1 (rice)	182	162
A2 (vegetables/cotton)	281	92
A3 (oilseeds)	150	110
Increasing costs of peak labour demand (γ)	1.85	1.71
Cost factor land (β)	2.13	1.40

It is important to note that Eq. (1) implies a non-linear relationship between crop water use and crop yield. This is in line with Liu et al. (2002) and Tuong and Bouman (2003), but it has been suggested that this relationship may also be linear (see for example Doorenbos and Kassam, 1979; Perry et al., 2009). Given that constant returns would reduce WSD benefits, we are confident that using the figures presented in Table 5 is in line with our aim of estimating a scenario of maximum WSD benefits for assessing the impacts of WSD at basin scale.

4. Results

Using the figures presented in Table 5 to estimate the shadow price of crop water use, the initial shadow price of water (i.e., before WSD investments) is 4.4 Rs/m^3 upstream and 4.3 Rs/m^3 downstream. Given the limitations of our analysis, this is surprisingly in line with the estimates made by Shiferaw et al. (2008) who, based on a micro-econometric model of crop-water productivity, estimated an average value of crop water use in the same region of 4.1 Rs/m^3.

Also, in line with our expectations, the value of crop water use is initially higher in up- than in downstream locations. As mentioned before, this is typical for the Musi sub-basin, where farmers produce relatively high value crops for the nearby urban market. In fact, Hellegers and Davidson (2010) argue that in the Musi sub-basin the value of agricultural water use upstream is roughly double the value of agricultural water use downstream. The difference can be explained by the fact that Hellegers and Davidson (2010) used model estimates of the quantity of irrigation water applied, and not crop evapotranspiration. Applied irrigation water includes both crop water use and any excess irrigation water, and especially in surface water irrigation systems the application of excess irrigation water is often high. This is especially true for flooded rice fields, which dominate in the lower part of the basin, including the Nagarjuna Sagar command area. Shiferaw et al. (2008) also use irrigation water applied, but in the groundwater irrigated upstream region the amount of excess irrigation water is much less. The zonal-average values of irrigation water of Hellegers and Davidson (2010) are also significantly lower (average 3.3 kharif and 2.04 Rabi season), which makes sense given that different approaches were used. Still, their results are in line with our expectation that the value of crop water use upstream is higher, and we will pay specific attention to their findings in the discussion of results.

In order to assess the welfare impacts of alternative investment levels we had to make an assumption about the shape of the WSD investment cost curve.[10] Assuming a linear cost function and a maximum WSD investment level of 200 USD/ha (i.e., twice the current investment level), the maximum amount of water that could be harvested would be 30 MCM. From a hydrological point of view, this seems like a realistic amount. In the catchment area, annual runoff was on average 7.5% of rainfall during 1994–2003 (Biggs et al., 2007),[11] and with a catchment area of 2111 km^2 and an average annual rainfall of approximately 890 mm, this would amount to a total run-off of approx 141 MCM, or more than 4 times the suggested amount. From a financial perspective, a maximum investment of 200 USD/ha also seems realistic: WSD investments generally range between 50 and 200 USD/ha. Using these figures to estimate the impact of five different WSD investment levels, Table 6 presents impacts of WSD in terms of changed cropping patterns.

Table 6
Modelled changes in cropping pattern (in ha) resulting from WSD investments.

	6 MCM	12 MCM	18 MCM	24 MCM	30 MCM
Upstream					
Rice	+154	+230	+305	+380	+454
Vegetables	+252	+376	+499	+620	+741
Oilseeds	+214	+319	+423	+526	+629
Downstream					
Rice	−170	−255	−340	−425	−510
Cotton	−186	−279	−371	−464	−557
Oilseeds	−148	−222	−296	−369	−443

Table 7
Estimated annual benefits of WSD (in million USD).

	With 20% efficiency gain	Without efficiency gain
6 MCM	0.14	0.02
12 MCM	0.27	0.02
18 MCM	0.40	0.02
24 MCM	0.52	0.01
30 MCM	0.63	−0.001

Table 8
Modelled changes in up- and downstream shadow prices by WSD investment level (Rs/m^3).[a]

	Base	6 MCM	12 MCM	18 MCM	24 MCM	30 MCM
Upstream	4.40	4.36	4.31	4.27	4.24	4.20
Downstream	4.30	4.30	4.30	4.31	4.31	4.31

[a] 1 Rs = 0.02 USD.

The welfare impact of the predicted change in cropping patterns is presented in Table 7, accounting also for the possibility that WSD has no efficiency effect.As the results in Table 7 indicate, benefits are sufficient to compensate downstream losses, even when WSD fails to create an efficiency gain. However, this still excludes the costs of WSD investment. Benefits decrease as WSD investment levels rise, which can be explained by the fact that at higher WSD investment levels the economic value of crop water use in the upstream region falls (as water becomes less scarce). At higher investments levels, the net benefit of WSD even becomes negative when WSD has no efficiency gain because downstream users lose more than upstream users gain (Table 8).

To calculate the net present value of the costs and benefits of WSD, we also had to make an assumption about the expected lifetime of WSD investments and the appropriate discount rate. With regard to the expected lifetime of WSD investments we assume that without maintenance the expected lifetime is 10 years. With maintenance, the expected lifetime increases to 25 years, assuming that maintenance is undertaken every 5 years at 5% of the investment cost.[12] Given that the State Bank of India uses a 10% interest

[10] Clearly, these are only rough assumptions which we make to get an indication how different WSD investment levels affect the shadow price of crop water use and, thus, the impact of WSD. Further research is required to analyze the shape of the WSD cost curve and the related water harvesting effect.

[11] This runoff coefficient is typical for semi-arid basins, including other watersheds in the Krishna Basin (Biggs et al., 2007).

[12] Clearly, this is a very rough assumption, but its sole purpose is to assess whether extending the lifetime of WSD investments affects outcomes in a significant way. We do not account for the maintenance costs of the downstream irrigation system since no data were available. Including the costs of downstream maintenance might

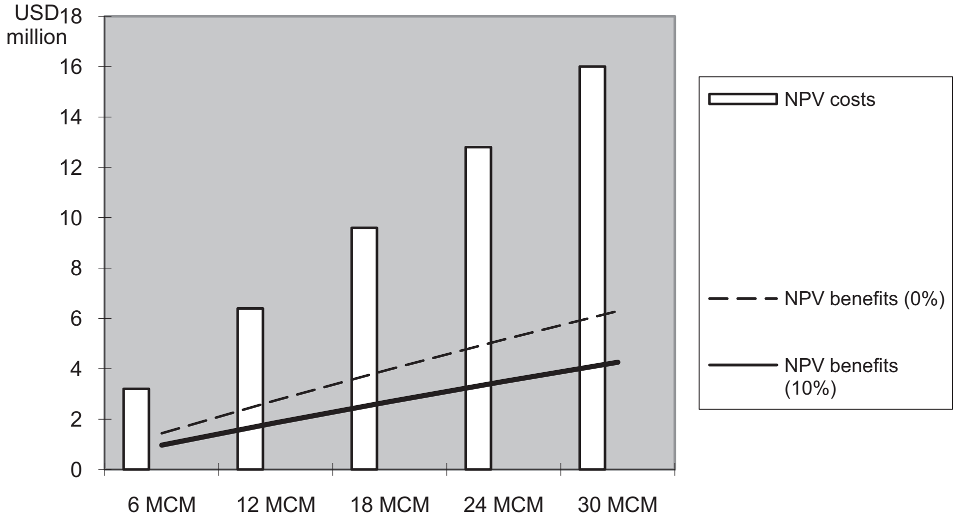

Fig. 2. Net present value (NPV) of watershed development investment in the Musi sub-basin without maintenance and with varying discount rates. Numbers in parentheses in the legend indicate the discount rate.

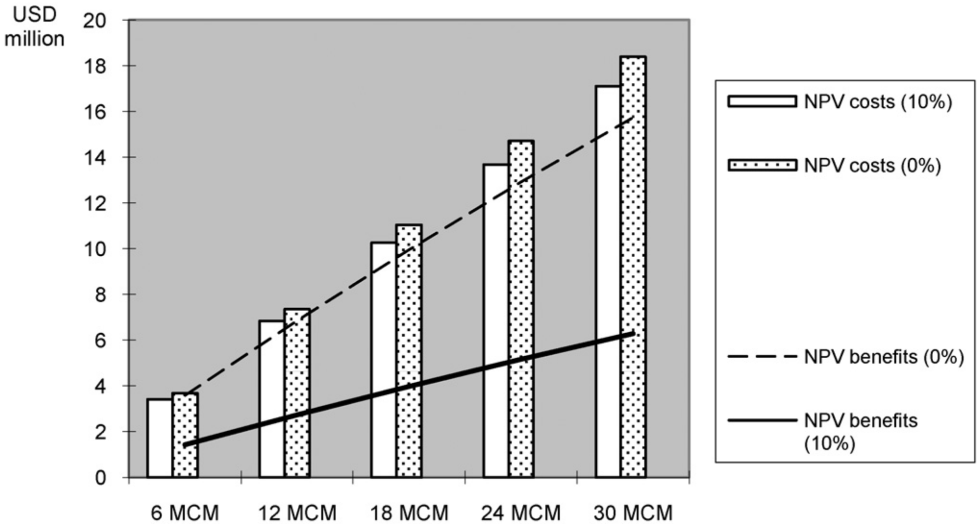

Fig. 3. Net present value (NPV) of watershed development investment in the Musi sub-basin with maintenance and varying discount rates. Numbers in parentheses in the legend indicate the discount rate.

rate on its agricultural loans, a 10% discount rate seems appropriate, but we calculate costs and benefits for a 0% discount rate too. Figs. 2 and 3 illustrate the net present value of WSD cost and benefits, for different lifetimes and discount rates.

Interestingly, even when the lifetime of WSD investments is extended (resulting in more benefits) WSD generates insufficient returns to payback investment costs. Hence, even when the shadow price of upstream crop water use exceeds the shadow price of crop water use downstream, WSD benefits are insufficient to cover downstream losses and payback WSD investment costs. Before discussing the implications of these findings, we will first assess the robustness of results.

5. Robustness of results

At several points in the preceding analysis we reported that data were only indicative since we had a limited dataset and data were of varying quality. To test whether the use of alternative figures would significantly alter the results, we performed a Monte Carlo simulation using a random sample of 75–125% of the data. Except for α, γ and E, all other parameters were left to vary. Assuming data are uniformly distributed, we use an Excel-based Monte Carlo simulation model, running the model 5000 times per investment level (Barreto and Howland, 2006). We used the outcomes of the simulations to calculate the standard deviation of our earlier findings, to estimate the probability that WSD has a positive welfare impact at basin scale. In Table 9 we present the results.

Table 9
Probability that benefits ≥ full investment costs (10% discount).

	Without maintenance (10 years)	With maintenance (25 years)
6 MCM	42%	45%
12 MCM	34%	39%
18 MCM	27%	34%
24 MCM	20%	29%
30 MCM	14%	24%

The reported probabilities are one-sided *P*-values.

increase WSD benefits at basin scale.

The results in Table 9 indicate that the probability that WSD generates a positive welfare impact is considerable, even when investments are not maintained, but that this probability decreases at higher investment levels and does no exceed 45%.

Hence, even at low investment levels, the probability that WSD is welfare enhancing is, under the assumptions of our model, less than 50%. For the actual WSD investment level in the Musi-sub-basin (15 MCM) the probability of WSD being welfare enhancing is 30–40%. Using a 0% discount rate increases the probability that WSD is welfare-enhancing by 6–25% (depending on the WSD investment level), as future benefits get the same weight as present costs. This ignores the time preference of the current generation to use the scarce financial resources to generate a maximum level of short term pay-offs, but can be justified when investments significantly affect the welfare of future generations (Markandya and Pearce, 1991). In the example of WSD in the Musi sub-basin this, however, does not seem to be the case: as argued extensively in this article, rainwater harvesting in the sub-basin affects flows, not stocks, and investments benefit the current generation, not future generations. In cases where WSD does significantly affect stocks, for example when investments significantly reduce soil erosion, a lower discount rate may be appropriate, but in our case using the market discount rate seems the most appropriate choice.

6. Discussion

Watershed development is a popular type of investment in semi-arid and arid regions, but the basin-wide impacts have not yet been assessed. This article suggests that when water is scarce at basin scale, and when benefits are limited to a change in the availability of (irrigation) water, WSD is unlikely to enhance welfare at sub-basin scale. Accounting for some of the uncertainties surrounding our data, we estimated the probability that WSD is welfare enhancing to be less than 45%. This result does not consider potential stock-related benefits, like reductions in soil erosion, but given the focus on rainwater harvesting in the study region, we expect the stock-related benefits of WSD to be small. Investment in maintenance and larger gains in water use efficiency could improve outcomes, but are unlikely to make WSD welfare enhancing at basin scale.

Although the analysis has its limitations and is based on only a small set of empirical data, we are confident that our findings are robust. Generally, WSD projects target watersheds where the economic value of upstream agricultural production is much lower, and under such conditions WSD investments are even less likely to generate sufficient benefits to compensate downstream losses and pay back WSD investment costs. Only when, like suggested by Hellegers and Davidson (2010), the economic value of upstream crop water use is double the value of downstream crop water use might WSD improve welfare at basin scale. Given that the Hellegers and Davidson (2010) results do not seem to account for the possible welfare effects generated by any return flow of irrigation water that is applied in excess of crop water use, the chances that the economic value of crop water use upstream doubles the value of crop water use downstream are, however, small.

The different outcomes do indicate that the results are sensitive to both the definition of crop water use (applied irrigation water versus consumptive water use) and the large uncertainties in the water balance of an irrigation system, including crop (irrigation) water demand and transmission losses. Further research is required to gain better insight into the water balance of irrigation systems, but our model results account for a wide range of crop water use values, and the results are robust to this range. More attention for the inter-annual variability of water availability and crop water demand and more data on production costs, crop yields and prices could help improve the estimates. Data on the amount of water storage created under different WSD investment levels might improve the WSD cost curve and alternative model specifications might make it possible to estimate crop specific water intensity factors as well. Also, data on the costs of downstream irrigation maintenance could help fine tune the cost analysis, but we do not expect that these changes would change the core message of this article, i.e., that harvesting rainwater in water scarce basins is unlikely to improve welfare at sub-basin scale.

The basin-scale welfare impacts of WSD might change if WSD has important stock-related benefits like reduced soil erosion, which would not only result in additional benefits but might justify a lower discount rate as well. Also, an argument in favour of targeting WSD to remote, low agricultural value watersheds is that it could help alleviate poverty by increasing the economic returns per ha. Fan et al. (2000) conclude, however, that investments in WSD are not effective for alleviating poverty, and that to improve the value of agricultural production in remote watersheds, investments should be targeted at roads, education and agricultural research and extension services instead.

Thus, especially in the light of the ongoing investments in climate change adaptation, which tend to focus on rainwater harvesting and water storage investments upstream, our article suggests that the cumulative effect of numerous small investments in rainwater harvesting could reduce the availability of water downstream and, thus, reduce welfare at basin scale. Especially because the downstream regions of most river basins are crucial for food production (Molden et al., 2001), it is important that the potential externalities of upstream investments in rainwater harvesting are adequately addressed.

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